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Special: Der weltberühmte Physiker im persönlichen Interview

Mit *Spotlights* von

Jürgen Heinze zu **Ameisen aus der Karibik** und

Christoph Wagner zu **Sigmar Polke**

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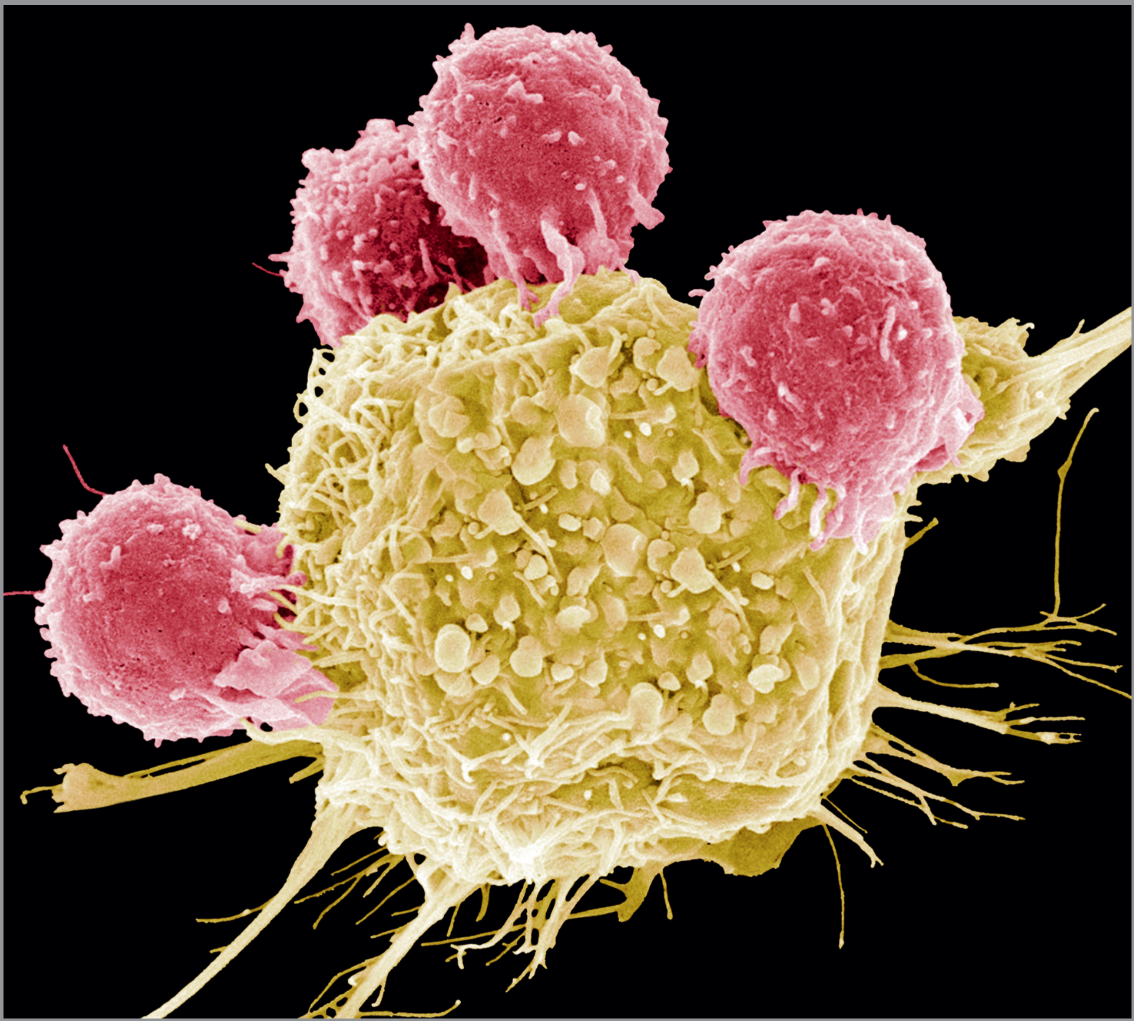

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Emily Whitehead ist berühmt. Wer aktuelle Fotos recherchiert, findet ein junges Mädchen, gerade mal 12 Jahre alt, frischer Teint, leuchtende Augen, offen, lebenslustig. Niemand käme auf die Idee, dass Emily vor sechs Jahren akut um ihr Leben kämpfen musste. Eine neue Krebsimmuntherapie hat ihr junges Leben gerettet.

Das Wissenschaftsmagazin Science titelt in der Dezember-Ausgabe 2013: „Krebsimmuntherapie – Durchbruch des Jahres“ und weiter *„T cells on attack“*. Emily verdankt ihr Leben ihren Immunzellen (T-Zellen), die im Labor gezielt zur Bekämpfung von Leukämiezellen verändert wurden. *„T cells on attack“* umschreibt gleich mehrere Phänomene: (i) Fundamental neue Ansatzpunkte in der Krebstherapie; (ii) die Eliminierung von Krebszellen durch neu programmierte T-Zellen (s. Titelbild); (iii) aber auch Über- und Fehlreaktionen des veränderten Immunsystems, die noch schwer zu prognostizieren und kontrollieren sind.

Die Medizinische Fakultät der Universität Regensburg (UR) hat rechtzeitig die Weichen gestellt, um die Krebsimmuntherapie international wettbewerbsfähig mit zu gestalten. Mehrere klinische, von der Deutschen Forschungsgemeinschaft (DFG) geförderte Forschergruppen haben dieses Thema stabil in Regensburg verankert. Das neue Regensburger Centrum für Interventionelle Immunologie wird mit drei in der Universität integrierten Lehrstühlen eine nachhaltig erfolgreiche Grundlagenforschung sicherstellen. Und das auf dem Klinikcampus angesiedelte José-Carreras-Centrum bietet mit der arzneimittelgerechten Anreicherung und Programmierung von Immunzellen beste Voraussetzungen für die Translation neuer Erkenntnisse in die Klinik.

Gemeinsam mit den Einrichtungen des Universitätsklinikums Regensburg und ergänzt durch ausgesuchte Teams der Universitäten Erlangen und Würzburg gelang nun unter Regensburger Federführung die Akquise eines von der DFG geförderten Sonderforschungsbereiches (SFB). Im Fokus dieses von Wolfgang Herr, Klinik für Innere Medizin III, koordinierten SFB stehen bislang ungelöste Herausforderungen bei der Immunzelltherapie von Leukämie- und Lymphompatienten. Der neue SFB sowie einige an der hiesigen Universität bearbeitete Fragestellungen werden in dieser Ausgabe vorgestellt.

© UR/Roswitha Kerzdörfer

Ein weiterer Themenfokus dieser Ausgabe: Ein Portrait des Physikers und Pulitzer-Preisträgers Douglas Hofstadter, dem 1974 als Doktorand während eines Gastaufenthaltes an der UR erstmals die Berechnung des Energiespektrums von Kristallelektronen in einem Magnetfeld gelang, heute berühmt als „Hofstadter Butterfly“. Anschaulich stellen Ferdinand Evers und Klaus Richter, Institut für Theoretische Physik, in ihrem Artikel die Bedeutung von „Hofstadters Schmetterling“ in den Kontext der 70er Jahre und zeigen den paradigmatischen Charakter der Doktorarbeit auf. 40 Jahre später, „zurück in Regensburg“, spricht Douglas Hofstadter in einem Interview mit Klaus Richter über seine Erinnerungen, Chopin, künstliche Intelligenz und seine ganz persönliche Metamorphose vom Physiker zum Kognitionswissenschaftler.

Ausgewählte Highlights aus der Moraltheologie zur Prinzipienethik in der Medizin und aus den Neurowissenschaften zur Visualisierung des Riechens runden das Spektrum dieser Frühjahrsausgabe ab. Neu eingeführt haben wir mit dieser Edition die Kategorie „Spotlights“ – aktuelle wissenschaftliche Themen in Wort und Bild prägnant für Sie aufbereitet.

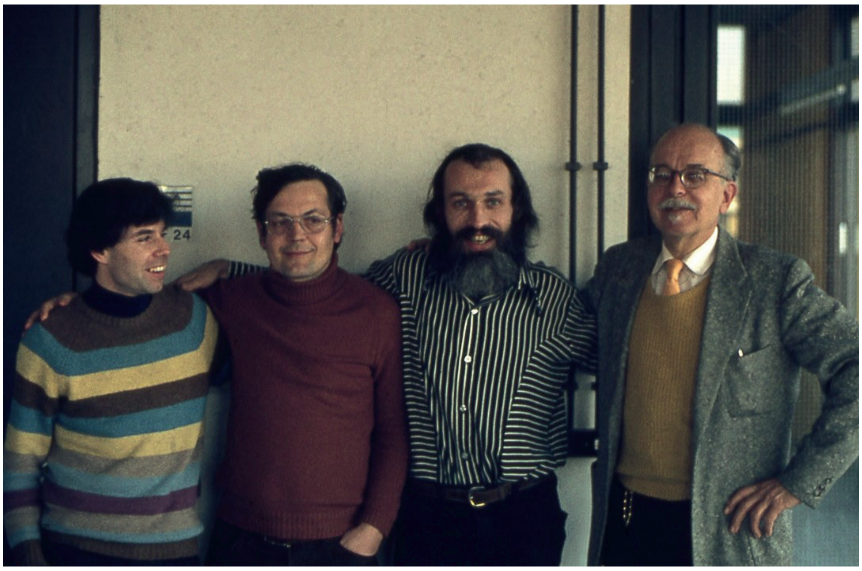
Ralf Wagner
(Redaktionsleitung)

Douglas Hofstadter (zurück) in Regensburg

Das folgende Interview ist die gekürzte Fassung eines Gesprächs, das Klaus Richter am 19. Oktober 2017 mit Douglas Hofstadter anlässlich dessen Besuchs in Regensburg geführt hat.

Klaus Richter: Doug, when you were doing your doctoral work, you spent the winter term 1974/1975 in our Physics Department, accompanying your Doktorvater Gregory Wannier, a distinguished solid-state theorist. Wannier was taking a sabbatical here on the invitation of Gustav Obermair, who at the time was a very active researcher and today is professor emeritus. From a memoir you wrote about those days, I got the impression that your stay in Regensburg was not very happy. On the scientific side, you had to strongly defend your ideas and your work from very harsh criticisms by your own doctoral advisor.

Douglas Hofstadter: That's certainly true, although at the beginning of my stay here I had no ideas at all to defend, and wasn't confident that I ever would have any!



4 Douglas Hofstadter an der Fakultät für Physik: *„The Regensburg group"* 1974 (v. l.) Douglas Hofstadter (als Doktorand), Alexander Rauh, Gustav Obermair, Gregory Wannier (Gastprofessor aus Eugene, Oregon). Das Foto wurde im heutigen Großraumbüro der Theoretischen Physik aufgenommen. © Privatarchiv Douglas Hofstadter

And on the personal side, I remember you wrote: "My best friend was Frédéric Chopin, late every night …" This sounds quite melancholy. How was your time here in Regensburg? Have you returned with mixed feelings after more than 40 years?

Well, yes, I must confess, I do have mixed feelings. It's not just that I had to defend my ideas when my *Doktorvater* was skeptical and harsh towards me. When I first arrived here in early September 1974, I felt very inferior. I was the only student in a research group with three professors – Gregory, Gustav, and Alexander Rauh *(damals Privatdozent; Anm. der Red.)*. Every day we four would meet in one of their offices *(siehe auch* **[4]***; Anm. der Red.)* and the three professors would discuss their ideas, writing equations on the board and proving theorems; all this seemed extremely sophisticated and far above me. I felt incapable, incompetent, and fearful of never being able to contribute.

And yet you had a strong mathematics background and had studied particle physics for a few years. You probably had a much deeper background than most Ph.D. students do these days.

Well, yes and no. The mathematics I loved the most and had studied the hardest was number theory, which was thought to play no role in physics, so it didn't seem relevant. I remember that when I became a graduate student in physics, one day some of my fellow students were talking about Hermitian and unitary matrices. As a math student, I had never run into such things, and the same was true of other mathematical ideas commonly used in physics, so actually I wasn't all that well prepared. In Regensburg, I felt far below Gregory, Alexander, and Gustav. And moreover, at that time the Vietnam war was still going on, and among many German students there was a strong anti-American feeling.

Even among the doctoral students in the Physics Department?

Yes, the visceral anti-Americanism radiated by a few of them caught me very much by surprise. It slowly evaporated, luckily, but at the beginning I felt ostracized by certain students who had pigeonholed me incorrectly, never suspecting I had exactly the same anti-war feelings as they did. Their simplistic stereotyping of me as "bad person" made me feel uncomfortable, although by the end we were quite good friends, so that was a positive thing for all of us.

On top of that, the building I was living in was not a student dormitory, but a workers' residence, and in the first week, when I went to take a shower, I found human excrement on the floor of the shower. This disgusted me, and as a result I never took a shower there, but always just washed myself using the sink in my own room. A few weeks later, someone knocked at my door around midnight, and naïvely, I opened it. It was a loud, angry drunkard who tried to barge into my room. Maybe he thought it was his room – I don't know. All I know is that he was frighteningly strong, and he pushed and pushed, and I had to push back with all my might to keep him out. Luckily I finally succeeded and managed to shut the door and lock him out. As you can imagine, all this was very disturbing to me.

But in compensation, one night at midnight, I randomly discovered a half-hour radio broadcast of Chopin piano music wafting all the way from Radio Warsaw, and it turned out to be a nightly program. Ever since childhood, Chopin had always been my favorite composer, so this was a great find. From that day onward, I used to tune in every night at midnight, and I even recorded all the broadcasts on cassette tapes, which I still have at home.

The signals came floating through the night air from far away – first over the plains and mountains of Poland and then over Czechoslovakia – and so the music would fade in and out, which was of course distressing, but ironically, it also made every single note of the music feel precious, because each one was so vulnerable, so easily crushed. The show had two announcers – a man with flawless British English and a woman with flawless French – and I grew very fond of them, almost as if they were my friends (especially the woman!).

One day, I learned there was a music school here at the *Uni*, so I started going there almost every day to play piano – especially Chopin. So by day, Chopin was my friend in the practice rooms, and late at night over the radio.

I also started studying the Polish language while living in Regensburg, and at the end of my stay, I took a train trip to Poland and even spoke a tiny bit of Polish while there. In fact, one day I dared to call up Radio Warsaw and told whoever answered about my love for their nightly Chopin program, and then asked if I could come and meet the two announcers. I was told I would be very welcome to visit the station and meet those people. I was excited!

A day or two later, I took a bus across Warsaw to the imposing Radio Warsaw building, and walked into the spacious hall. There I was greeted by a friendly fellow named Michał Kubicki, who spoke superb English and said he would like to interview me: after all, an American physics graduate student living in Germany and faithfully listening to Radio Warsaw's broadcasts of Chopin music, night after night, was most unusual and surprising. I was terribly flattered; in fact, this would be my first interview ever!

Michał Kubicki recorded our brief conversation, in which I explained how I would tune in every midnight, with Chopin's music poignantly fading in and out, reminding me of Poland's rough history, with the country as a whole having so often faded in and out over the centuries. (Any Pole would know just what I meant.) After the interview, instead of being introduced to my "friends" the show's announcers, I was taken to meet Maria Nosowska, the woman who had created the program 25 years earlier and ever since then had curated it, day in day out. Together, she and I listened to Chopin music for a few hours, speaking French the whole time. It was an unforgettable visit, and for several years afterwards, Maria Nosowska and I kept in touch by handwritten letters.

"I couldn't help but feel that the true 'language of physics' was German. I even felt, irrationally, that one couldn't really understand physics unless one spoke German!"

The evening of my return to Regensburg, the little interview with Michał Kubicki was scheduled to be broadcast, so I rushed from the train station to my tiny dorm room and anxiously turned on my radio. Only minutes later, to my amazement, there was my own voice, soaring across the night skies from far-off Warsaw, describing how the precious notes of Chopin always faded in and out on my radio – and as I listened, my voice itself was fading in and out, just as Chopin's music had done. This strange loop of myself in Regensburg listening to myself in Warsaw a few days earlier, with my own words now fading in and out as I was describing Chopin's powerful notes fading in and out, was the most magically poetic moment of my entire Regensburg stay, I would say.

It was also in Warsaw that I gave the first colloquium in my life, sharing my initial discoveries about the infinitely-nested spectrum with physicists at the University of Warsaw's Institute for Theoretical Physics. This was a great boost to my confidence, because no one there ridiculed my claims at all.

How did your host, Gustav Obermair, treat you during your stay here?

Gustav was warm and welcoming in many ways. Thanks to him, I became a "VDwA" (*Verwalter der Dienstgeschäfte eines wissenschaftlichen Assistenten*), and as such I wound up teaching a small laboratory course that semester – in German! I was quite proud of myself for that, although it wasn't nearly as hard as teaching a regular course would have been. (Amusingly, I seldom understood what my students said, since they spoke Bavarian!) Also, a convention in the Lehrstuhl Obermair was that everyone used the informal "du" with everyone else, no matter what their status was. That was surprising but nice.

I also remember how Gustav loved his mother tongue, and how he would spontaneously improvise long, flowery German sentences at the very end of which he would drop two or three verbs that even native speakers were probably not anticipating. I couldn't quite follow Gustav's beautifully intricate sentences, but I took great pleasure in hearing his virtuosic mastery of his native language.

The two people in Regensburg with whom I developed the closest friendship were Alexander Rauh and his wife Merve. Many weekends, I would trudge up into the country hills to their house, carrying along with me some delicious pastries purchased at my favorite *Konditorei* near the train station, and then Alexander and I would drink coffee, eat *Kuchen*, and play chess, and the three of us would always speak German together, which was very good for me.

How well did you speak German at that time?

Oh, fairly poorly at the beginning, but fairly decently at the end of my six months. I loved languages, and had studied German for two years at Stanford University, and in Regensburg I worked like the devil to improve my German.

Incidentally, when I was growing up, the field of physics was still deeply under the influence of the German language. Thus, on the bookshelves in my Dad's

5 Douglas Hofstadter (l.) und Klaus Richter im Oktober 2017. Foto: Jörg Mertins

office (*Robert Hofstadter, berühmter US-amerikanischer Physiker und Nobelpreisträger; Anm. der Red.*), I used to see various books in German – for instance, I remember *Wellenmechanik* and also *Atombau und Spektrallinien* by Arnold Sommerfeld, and Max Born's classic *Optik.* My Dad had studied from them all! And German was of course the language of Einstein, Heisenberg, Schrödinger, Pauli, and so many other greats. One of our closest friends at Stanford was Felix Bloch *(berühmter Schweizer Physiker und Nobelpreisträger; Anm. der Red.)*, who had been Heisenberg's first doctoral student, and who was the founder of solid-state physics. I couldn't help but feel that the true "language of physics" was German. I even felt, irrationally, that one couldn't really understand physics unless one spoke German! So to me, the prospect of coming to Germany to do physics was exciting. Although I spoke only haltingly when I arrived, I was very eager to get better, so I studied hard. For instance, I spoke German quite often with a handful of non-physics students whom I met.

And last night, finally back in Regensburg after 42 years, you gave a long talk in German called "Licht bei Einstein; Einstein bei Licht".

Yes. In fact, giving a physics lecture in German, the language of quantum mechanics, was a long-time ambition of mine – a dream come true, even.

And you spoke nearly without any accent and with such a rich vocabulary.

Thank you for such kind words! But I must say, I prepared last night's lecture for weeks. In fact, I gave four practice versions of it to friends in Vienna before arriving in Regensburg. It's not as if I just improvised it all off the cuff …

You told me your talk was based in part on the German translation of one chapter of your recent book "Die Analogie", co-authored with Emmanuel Sander, in which the two of you put forward the idea of analogies as "the fuel and fire of thinking". I agree that analogies are extremely important in my scientific thinking. However, just using analogies might not be enough to let one discover something really new.

I am convinced that analogy suffices. I would simply say that analogies on multiple levels and of multiple sorts have to be used – not just one analogy alone. To my mind, analogy-making is the key activity in the mind of a creative physicist – or mathematician – or writer – et cetera. Analogy-making is the crux of thinking!

One's analogies are of course rooted in one's experiences. So, does the role played by analogies evolve over the course of a human life? Do even babies employ analogies?

To be sure, babies draw very simple analogies to things they need. These are blurry proto-analogies. But as their experience builds up, their set of categories and experiences gradually enlarges and sharpens, and they make fresh new analogies to try to understand things they haven't seen before. For instance, a young child might see an unfamiliar animal and say "horse" or "big dog". Whether it's correct or not, this is an analogy. Children are constantly making humble analogies – some right, some wrong. But as their set of experiences widens and deepens, the analogies they make grow ever subtler.

Drawing analogies is crucial to human mental life, but what about computers? Could you imagine feeding a lot of hu-

man knowledge into a computer and then writing a sophisticated program allowing the computer to come up with analogies similar to ones that a human mind might come up with?

Well, for four decades, my research, with my graduate students, has been all about developing computer models of analogy-making. But we haven't tried to get computers to make analogies in the unlimitedly complex real world. Instead, we've studied analogy-making in "microdomains". (For example, "If ***abc*** changes to ***abd***, what does ***ppqqrrss*** change to?") Despite the tininess of all our domains, elegant and subtle analogy questions can nonetheless be posed in them. (For instance, "What does ***xyz*** change to?" or "What does ***mrrjjj*** change to?") Understanding how insightful answers to such questions bubble up from some hidden wellsprings in one's mind is a deep mystery. And I'm glad that it has remained so mysterious even after decades of our research, because I recoil at the thought that computers are approaching the level of human intelligence. So every time I think about how hard it has been for me and my students to allow computers to come up with insightful analogies even in our tiny microdomains, I'm hugely relieved. In fact, I'm delighted when, despite all our intense efforts to give our models intelligence, they act dumb and show a total lack of insight. Such failures bring me relief and pleasure.

So you don't want to see computers achieve human intelligence?

The thought frightens me. To me, it was very sad to see world chess champion Gary Kasparov lose to Deep Blue in 1997 – and when, 20 years later, the great Go player Lee Sedol lost in Go, that made me even sadder. On the other hand, I recently wrote a couple of articles about Google Translate in which I showed how weak it is, even though it often gives a very good first impression. But when you look more closely, you find it often performs ridiculously poorly – and once again, that feebleness gives me a huge sense of relief.

On the other hand, shouldn't one consider the possibility, even if it's unlikely, that at some stage computers might reach our human level? And to be prepared for that, shouldn't we be studying the risks of artificial intelligence (AI), exploring various scenarios for what might happen in the future, much as in climate research? We shouldn't just wait passively, should we?

No. I agree with you that AI is a danger – hopefully not an imminent one, but a danger. One serious problem, though, is that if you get some researchers to refrain, there will always be others who will eagerly jump in, in their place. Or if one country says, "We are not going to do this", then another country will jump in, because there's money to be made. Unfortunately, it's money that drives most AI research, and we're not going to be able to change that. And so, unfortunately, I think there's no stopping it. Still, no one knows if AI will reach or surpass the human level soon, or if that's still very far away, as I hope.

"In the mid-1980s I stopped calling myself an AI researcher as I realized my real goal wasn't to make computers smart. It was to understand the human mind, designing computer models to try to approximate certain aspects of thought."

In the late 1970s, just a couple of years after my Regensburg time, when I was finishing up my book *Gödel, Escher, Bach* and starting to do research in artificial intelligence, I believed that human intelligence was the ultimate, long-term, limiting goal for computers. I imagined that computer intelligence would only very slowly – perhaps over hundreds of years – approach the human level, always from below, like a gentle curve asymptotically approaching a horizontal line from underneath. But I never thought computers would surpass humans. I didn't even think they would be likely to surpass humans in chess! (I was very wrong there.) A couple of decades later, the fact that in certain domains computers were indeed surpassing humans started to worry me.

In the mid-1980s, I stopped calling myself an AI researcher, as I realized my goal wasn't to make computers smart; it was to understand the human mind, designing computer models to try to approximate certain aspects of thought. I had always felt unbounded admiration for marvelous creative minds like those of Bach, Chopin, Pushkin, Euler, Galois, Einstein, Heisenberg, Kandinsky, Monet, Gershwin, and many others. In fact, I've always admired the human mind in general (not just the minds of geniuses). I hold the human mind in a kind of reverence, and for that reason, I have zero interest in seeing computers become rivals to human minds – in fact, I'm profoundly troubled by the idea.

What you're saying strikes me as quite ironic, because in the 1980s, your famous book "Gödel, Escher, Bach" (GEB) was seen by many as claiming that intelligence is not, in principle, restricted to just humans but can, in principle, be attained by machines.

Well, in my view, machines can, *in principle*, be as intelligent as humans – but in GEB I stated that although we humans are trying very hard to understand how our minds work by building computer models of mental processes, we still have a long, long way to go. I am of course aware that many people have called GEB "the bible of artificial intelligence", but I've never felt comfortable with that rather silly label. However, I'm pleased, and even proud, that GEB has inspired many to ponder the relationship between the human mind and computers.

A central theme of GEB is recursion and self-reference (damit ist gemeint, dass in einer natürlichen oder formalen Sprache eine Aussage, Idee oder Formel auf sich selbst Bezug nimmt; Anm. der Red.). In complexity theory – for instance, in models like John Conway's "Game of Life" – the occurrence of structures of that sort is considered to be a hallmark of the border between order and disorder, sometimes called "the edge of chaos". ("Game of Life" ist ein einfaches mathematisches Modell, in dem die auf einem Schachbrett-Gitter angeordneten Zellen eines dynamischen Systems durch Werte wie z. B. „0" für „tot" und „1" für „lebendig" repräsentiert werden; Anm. der Red.) Do you see a connection between chaos and self-referencing structures?

In a way. In one chapter of GEB, I discuss the recursive Q-sequence, which I invented in the 1960s. Its definition is very simple, but its behavior is surprisingly chaotic. I have always been fascinated by mysterious patterns like that, which lie somewhere between order and chaos. This kind of intimate mixture between order and chaos is perhaps the height of mathematical beauty, at least for me. All this is related to the goal of getting computers to become animate, so to speak, by which I mean getting them to be creative or unpredictable. Trying to make a totally predictable, orderly machine act unpredictable and chaotic is a very interesting, quasi-paradoxical goal.

You mentioned beauty at the end of your talk last night. How can one recognize beauty in science? Probably there is no easy answer to that.

No, there's no easy answer. During my first years as a physics student, when I was learning great ideas developed by pioneers like Newton, Faraday, Maxwell, Carnot, Clausius, Einstein, Bohr, Dirac, Schrödinger, and so on, I thought physics was truly beautiful. But when I started to study particle physics, I was astonished to find it ugly, filled with arbitrary constants and strange ideas that made no sense to me. And the more deeply I got into it, the uglier I found it. Yet when I complained about some idea I found horribly ugly, my professors would reply: "Ugly? To me it's beautiful!" I would try to explain my feelings, but I couldn't, so in the end we just had to agree to disagree. Even today, I still find many ideas in particle physics hideous; they still inspire a feeling of nausea or disgust in me. And I still can't really explain why they repel me so strongly.

What about the symmetries that play such a key role in particle physics? Aren't they beautiful?

Yes, sure, I like all sorts of symmetries, but particle physics is filled with *broken* symmetries, which I find very ugly.

But shouldn't one enjoy breaking symmetries slightly, maybe also in music?

Symmetry isn't a central goal in music. Of course one can play around with symmetry in music – for instance, making curious kinds of canons that sound identical backwards and forwards, which is amusing, but basically doing that is just clever gameplaying. For me, serious music has little to do with symmetry.

But coming back to beauty in science, I would say the search for beauty pervades the activity of doing mathematics or physics. My Dad, toward the end of his life, made an interesting observation as he reflected back on his early days doing electron-scattering from nuclei, in the 1950s. He said: "We started out scattering electrons off of heavy nuclei like gold, and we gradually moved down the periodic table, from gold to iron to calcium, and so on. It was a very special moment when we came to carbon, since carbon is the core of life. And then we came to the *helium* nucleus – the alpha particle. Here we were, studying the inner structure of the alpha particle by shooting a beam of electrons at it. To me, it was magical, because Rutherford, in 1910, in *his* scattering experiments, had shot a beam of alpha particles at gold atoms; that was how he discovered that atoms had tiny nuclei inside them." My Dad was expressing a very emotional reaction to certain nuclei. That was typical of him – he was emotionally touched by the beauty of scientific research and scientific discoveries.

"I myself, when I give talks, try hard to take the viewpoint of my listeners into account. (…) I give imagery, analogies, anecdotes, and humor. I sometimes even use poetry or ambigrams to arouse people's interest."

Do you think such emotional reactions still play a role in physics today?

I hope they do, but I have to say, I don't understand physics at all well today. Actually, I didn't even understand it well when I was plunged into it full-time, as a doctoral student. But there is something very different these days, which worries me. Today's students tend to get involved extremely early in very technical issues, becoming glib with fancy jargon, but losing sight of what's deep and fundamental. Today, mere undergraduates are pushed very hard to do research and publish articles, often with dozens of co-authors. That makes no sense to me. My friends and I didn't publish papers even as *graduate* students, let alone as *undergraduates*. It seems to me that when one is a student, one should read and read, savoring deep ideas, instead of just adding one's name to one paper after another; to me, that's misguided and pointless. But I'm a purist and I have old-fashioned views. I believe in the love of knowledge *per se*.

Another troubling tendency I see is that scientists and science students fling complicated and technical words and ideas about, without the least concern for clarity. For example, in this morning's symposium about the butterfly, a couple of the talks were far too technical for me – just complex equations and nonstop jargon. I felt utterly lost. The speakers weren't thinking about how a listener like myself would react to the extremely technical language they were using. Nothing was explained in down-to-earth, imagistic language that I could have understood. And this is so typical in physics today – and even yesterday.

When I was a physics graduate student in Oregon in the 1970s, I would eagerly attend all the departmental colloquia, hoping to hear exciting new ideas, but I was usually disappointed. I seldom understood much – the talks were usually far too technical. Sometimes, though, in the middle of a talk, a speaker might briefly offer a concrete, vivid analogy, capable of giving us listeners real insight – but all too soon the speaker would feel nervous about having turned informal and imagistic, and would quickly return to the dense technical style, because hiding behind the nearly impenetrable bastion of dense formulas and opaque jargon made them feel "safe". That's pretty sad.

I myself, when I give talks, try hard to take the viewpoint of my listeners into account. I'm not saying I always succeed, but at least I give imagery, analogies, anecdotes, and humor. I sometimes even use poetry or ambigrams to arouse people's interest. I try to communicate on a very visual, basic level, because I feel that deep down, there is something childlike in each of us.

Would you say that the focus on technical and formalistic aspects kept Gregory Wannier from understanding your discoveries back in the seventies?

Not exactly. Let me try to explain. Deep physicists like Wannier, Rauh, and Obermair were extremely insightful in certain areas of mathematics, and I was not. But as it turned out, the secret, in the special case of Bloch electrons in magnetic fields, didn't lie in the manipulation of equations – it lay hidden in a visual structure that nobody had thought of generating and looking at.

One day, not too long after I had arrived in Regensburg, I noticed, in the hallway of the Lehrstuhl Obermair, a desktop computer, which Gustav later called "Rumpelstilzchen" (*siehe* **[2]**), and I thought, "Hmm … maybe I can study this complex physical phenomenon not by manipulating equations, but by using this little computer to calculate the allowed energy levels for me." The only pathway I felt capable of following – namely, programming a computer – was quite simple-minded, compared with the high abstractions that Wannier, Rauh, and Obermair were dealing with. I hoped, though, that maybe I could gain some new kind of insight by *numerically* studying the behavior of the high-order polynomials that cropped up in the problem. (I certainly couldn't solve the polynomials formally!) So I wrote a program (it was actually quite a tricky program to write, because those polynomials fluctuate extremely wildly), and the little computer obediently calculated all sorts of numbers for me – the endpoints of the allowed energy bands. This is why Gustav called the machine "Rumpelstilzchen" – because it worked overnight creating metaphorical gold.

Using Rumpelstilzchen's "golden" numbers, I was able to plot by hand an amazing, intricate graph *(siehe* **[3]**) – the spectrum of Bloch electrons in magnetic fields, which I called "Gplot" ("G" for "gold"). After several weeks, I started to perceive fantastic patterns in Gplot that reminded me of patterns in the number-theoretical research I had done many years earlier – a perfect example of analogy-making in physics! Instead of manipulating equations, I was simply looking at the spectrum itself, as a visual picture on paper – something no one else had thought of doing. Today I find it astonishing that in 40 years of research into this fundamental problem, no one had ever tried doing that before. People were trying to understand what was essentially a visual object *without ever looking at it*! Instead, all they did was manipulate equations that *described* the spectrum without *showing* it. In retrospect, that was naïve.

But when I started using Rumpelstilzchen, I certainly didn't say to myself, "Oh, now I'm going to show everyone else that with a computer I can crack the whole mystery wide open!" Not in the least! All I thought was, "I'll try this approach, because it's the only one I'm capable of trying." And then I turned out to be lucky – very, very lucky. I had a "prepared eye", one might say, from my youthful number-theory explorations carried out a dozen years earlier, and that was an advantage that Gregory, Alexander, and Gustav didn't have.

"To my mind, analogy-making is the key activity in the mind of a creative physicist – or mathematician – or writer – et cetera. Analogy-making is the crux of thinking!"

This is why, when I showed Gregory a very sketchy, hand-plotted version of Gplot for the first time, in November of 1974, he didn't understand my ideas about it at all. When I told him I had discovered that it consisted of distorted copies of itself nested down infinitely deeply, he just shook his head sadly, and then, to my huge shock, he disparaged my ideas by calling them "numerology", and adding insult to injury, he even told me I couldn't get a Ph.D. with such unscientific silliness. This very tough conversation marked the beginning of my frustrating "battle" with Wannier, which lasted for nearly a year. Of course, as you know, Gregory finally changed his tune 100 percent, and even came to love the recursive structure of Gplot. That was quite a turnabout for someone who at first had condescendingly called it "numerology"! At first, though, he was convinced that computational studies couldn't hold a candle to formal theorem-proving, but luckily, he eventually changed his mind. To Gregory, what I was doing seemed almost childishly simple; he didn't realize that one's *eyes* could sometimes see things that one's abstract *mind* could never have imagined.

Perhaps my general point, not just limited to my personal story of discovering Gplot, is that being concrete, down-to-earth, and simple is something I rarely see in physicists. In fact, I rarely see it in the academic world in general, and that's very troubling to me.

You have known many famous scientists, like Gregory Wannier, Richard Feynman, Murray Gell-Mann, C. N. Yang, and of course your father and Felix Bloch. Did they do physics on a completely different level? Did they do it more intuitively, or did they profit from extraordinary skills?

It's true that over the course of my life, I've known many famous physicists, mostly through my Dad. That was a great honor and a great privilege. Of course they were all very different from one another, so I can't offer any general observations about their thinking styles.

But who impressed you particularly?

Well – one person who left a lasting impression on me was Professor John Powell at the University of Oregon. Whenever I would go to ask him a question in physics, he would listen very carefully and then perhaps scratch his chin, give a shy little smile, and then say: "Hmm … Let's see, I think I remember something about this ..." And then he would go up to his blackboard and start writing a little bit, just a few symbols, and he would explain the *ideas* behind his symbols very clearly. In contrast, most other professors, when I went to them to ask them questions that were driving me crazy, would instantly jump up to their blackboards, write down long equations, rattling off fancy jargon and technical terms a mile a minute – basically just putting up a smokescreen of vast erudition, but losing me totally in the process. John Powell, though, never did that, and I really admired his modesty. And in contrast to the others, he almost always put his finger on the crux of the problem and explained it beautifully and clearly to me. But despite his great mind, John Powell didn't become a famous physicist. Maybe it was just the luck of the draw. On the other hand, Felix Bloch, my Dad's closest colleague and great friend at Stanford, was very famous and certainly was one of the smartest people I ever met.

Did you ever talk about physics with Bloch?

Not too often. Our families as wholes would get together, so physics was not often a topic of conversation. In fact, during the 1950s, our families often skied together, in California's Sierra Nevada. That was very formative for me. Felix also played piano very well. This was something we shared. Sometimes I would play a little bit for him, and he would play for me, and that was great. It was a real thrill for me when, in January 1976, I gave Felix a signed copy of my thesis concerning Bloch electrons in magnetic fields. I will never forget how he casually said to me, after looking it over a bit, "You know, this problem is special because this number alpha you're using is the ratio of two natural frequencies in the problem – one of them due to the magnetic field alone, and the other due to just the crystal." I had had no idea of that fact. Until that moment, I'd always thought of alpha as the ratio of two magnetic fluxes. I didn't know it was also the ratio of two natural *frequencies*. That was a deep insight of Felix's, and he came up with it effortlessly. And yet, I will also always remember that a few years later, when I was writing an article about Rubik's Cube, which I found fascinating and profound, Felix didn't see any mathematical interest in it, let alone depth or beauty; he saw it merely as a colorful toy. It just goes to show that *de gustibus non est disputandum…*

In the summer of 1975, I had a long visit with the legendary Richard Feynman in his CalTech office. On his blackboard I wrote Harper's equation *(siehe die Gleichung auf Seite 37; Anm. der Red.)*, and in a flash Feynman said: "Oh, it's its own Fourier transform." It had taken me a couple of *years* to realize that! And then, when I showed him the graph of Gplot, his eyes almost popped out, and he instantly fell in love with it. We talked about Gplot for at least a couple of hours.

When I was growing up, many of the people who came to our house for dinner were physicists. What I loved about my parents' dinner parties was how the conversations would jump from politics to art to music to literature, and so on. All of our friends also loved nature. They loved hiking, they loved the world of culture, and they were interested in languages and in history. From this kind of thing, I grew up with the feeling that physicists were highly cultured people with sophisticated interests and great senses of humor.

Has this impression changed over the years?

Well, I haven't associated as much with physicists in recent years, but I still have the impression that they're very thoughtful people with broad interests. On the other hand, that goes against what I said earlier about how they use jargon and don't seem to know how to communicate. So I honestly don't know where the truth lies. As for myself, I don't feel that I ever truly was a physicist. I still mostly feel I was just very lucky to have spotted that lovely shell lying there on the beach and to have picked it up before anyone else did *(hiermit ist die Entdeckung seines „Hofstadter Butterfly"-Spektrums „Gplot" gemeint; Anm. der Red.)*. But I don't think spotting Gplot on the beach and picking it up made me a physicist; it just made me a lucky person!

In fact, if you don't mind, I would like to close with a poem I recently wrote about my great stroke of luck in Regensburg, way back in 1974. I wrote it in the form of an Onegin stanza (invented by Alexander Pushkin), and I called it "Gplot's Grace":

What happens if a crystal's laced with
  The lines of a magnetic field?
What spectrum will the world be graced with?
  What energies will nature yield?

It turns out that the matter's crux is
Determined by just what the flux is –
  p-over-*q* *q* bands begets;
  Non-ratios, though, give Cantor sets!

On hearing this, a physicist'll
  Declare it numerology;
  But once shown Gplot, all agree
Deep magic's lurking in a crystal!

  This gem I found by luck. That's why
  There but for Gplot's grace go I.

Doug, thank you very much for this interview.

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